ABSOLUTE MOTION PARALLAX WEAKLY DETERMINES VISUAL SCALE
IN REAL AND VIRTUAL ENVIRONMENTS

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ABSTRACT

The determinants of visual scale (size and distance) under monocular viewing are still largely unknown. The problem of visual scale under monocular viewing becomes readily apparent when one moves about within a virtual environment. It might be thought that the absolute motion parallax of stationary objects (both in real and virtual environments), under the assumption of their stationarity, would immediately determine their apparent size and distance for an observer who is walking about. We sought to assess the effectiveness of observer-produced motion parallax in scaling apparent size and distance within near space. We had subjects judge the apparent size and distance of real and virtual objects under closely matched conditions. Real and virtual targets were 4 spheres seen in darkness at eye level. The targets ranged in diameter from 3.7 cm to 14.8 cm and were viewed monocularly from different distances, with a subset of the size/distance combinations resulting in projectively equivalent stimuli at the viewing origin. Subjects moved laterally plus and minus 1 m to produce large amounts of motion parallax. When angular size was held constant and motion parallax acted as a differential cue to target size and distance, judged size varied by a factor of 1.67 and 1.18 for the real and virtual environments, respectively, well short of the four-fold change in distal size. Similarly, distance judgments varied by factors of only 1.74 and 1.07, respectively. We conclude that absolute motion parallax only weakly determines the visual scale of nearby objects varying over a four-fold range in size.

Keywords: visual scale, absolute motion parallax, space perception

1. INTRODUCTION

Despite a long history of investigation, the problem of how we perceive visual size and distance (visual scale) still remains very much a mystery, in part because the stimulus support for the determination of visual scale is far from established. Although a great deal of attention has been given to the binocular cues of convergence and binocular disparity in research on visual space perception, they surely are not essential to the perception of absolute size and distance beyond 10 m under normal circumstances. Consider that one's perception of scale when moving about in the "real world" is scarcely different with two eyes than with one. Similarly, looking at the Grand Canyon produces an experience of enormity that would hardly enthrall us if visual scale were to depend critically upon binocular cues. One is forced to the conclusion that monocular distance cues (e.g., motion parallax, height in the field, texture gradient, relative size, familiar size) must provide the primary support for the perception of visual scale.

This classic problem is receiving renewed interest by developers of virtual environments. The key question is this: What stimulus information is critical for conveying a sense of visual scale? A secondary question is whether perceived scale is more definite when the observer actually moves (providing proprioceptive and vestibular cues) than when the observer passively navigates through the virtual space by means of a Dataglove or some other pointing device. It might be thought that absolute motion parallax produced by active observer translation is the basis for the perception of scale. Our experiment, however, indicates that absolute motion parallax, when changes in angular size are minimized, contributes little to the perception of scale.

In evaluating the effect of absolute motion parallax, it is useful to compare the perceptual results with what might be obtained under two alternative (and extreme) hypotheses. The first assumes that subjects use absolute motion parallax to perceive egocentric distance correctly and, consequently, to perceive absolute target size correctly, according to size-distance
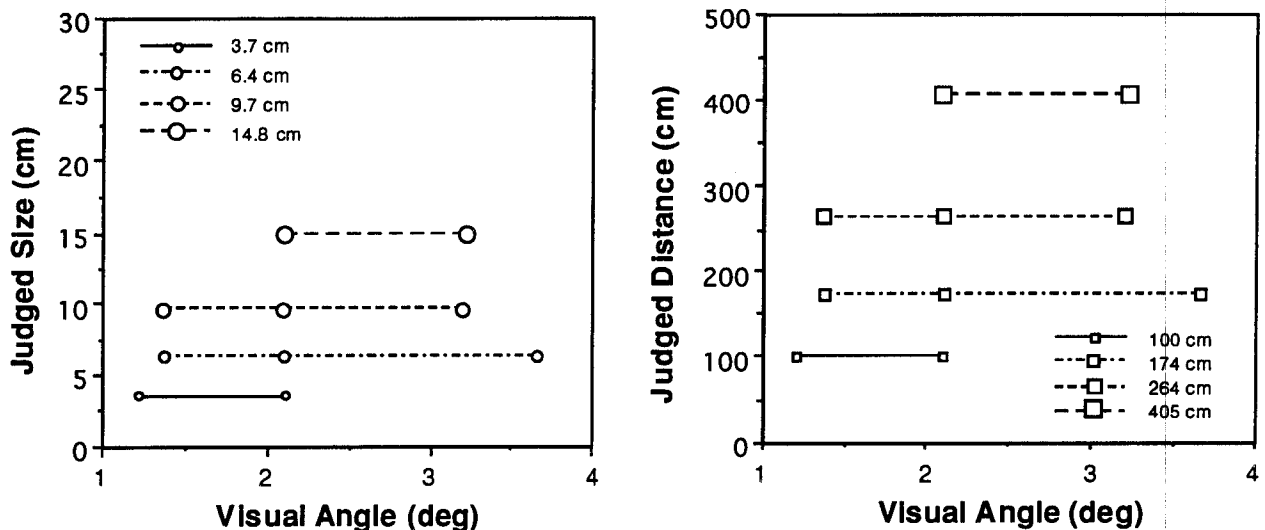
Figure 1. Depicts results that would obtain if size and distance were perceived correctly by the subjects.

invariance[1,2]. Figure 1 depicts the results that would obtain if size and distance were perceived correctly, using the physical target values of the experiment to be reported. Four different targets (glowing spheres) varying in diameter were presented at several different distances, such that for some combinations of size and distance, the targets subtended the same visual angle. According to this hypothesis, perceived size and distance exhibit a four-fold change in value in accord with the four-fold change in physical size and distance used; there is no dependence of these judgments on the angular size of the targets per se.

The other hypothesis assumes that there is no influence of absolute motion parallax on perceived distance. In this case, stimulus configurations matched in terms of visual angle in Figure 1 would be judged the same both in terms of perceived distance and in terms of perceived size; thus, the various curves in Figure 1 would collapse into one under this hypothesis. The precise shape and position of the function would depend upon other influences on perceived size and distance, such as the Specific Distance Tendency[3].

In the experiment we are reporting, we had subjects judge the perceived sizes and distances of targets viewed in both real and virtual environments. In each environment, we used real (and simulated) targets varying four-fold in size and then presented them at real (and virtual) distances so that for a subset of the conditions, visual angle remained constant, as is common in research on the perception of size and distance[4,5].

2. METHOD

2.1 Subjects

Six graduate and 4 undergraduate students were paid to participate in the experiment. Each of the ten participants was naive about the purpose of the study. The subjects were randomly assigned to either the real or virtual objects condition. Visual acuity was not tested, for the experiment involved monocular viewing of stimuli under conditions of impoverished visual resolution.

2.2 Apparatus

For the Real condition, we used styrofoam spheres covered with glow-in-the-dark paint. The room lights were used between trials to keep the paint charged and brightly glowing. The measured diameters of these four spheres were 3.7, 6.4, 9.7, and 14.8 cm. An adjustable tripod was used to fix the center of each sphere at each subject's eye-level for the entire experiment.

While viewing the real objects, each subject wore a pair of goggles that occluded his/her non-dominant eye and held a diffusing filter over the dominant eye. We used a filter that was strong enough to ensure that no texture and/or accommodative information would be of use to subjects at the nearest viewing distance.

For the virtual conditions, we sought to visually simulate the real objects by using a virtual display system of our own construction. There are three main components to our system: 1) the helmet-mounted display (HMD), 2) the graphics computer, and 3) the head-tracking sensors. Each component is described below.

The HMD we used is our own design. It consists of two Sony color LCD active-matrix television screens (model FDL-310) and lenses that produce collimated images for each eye. These LCD screens have a rated resolution of 320 lines by 240 lines (horizontal x vertical), but after accounting for the color mask the effective resolution is actually closer to 210 lines by 160 lines. Interfacing with the optics in our HMD loses even more resolution, leaving a final, effective resolution of 110 lines by 100 lines. When worn, each display subtends about 40° by 35° (horizontal x vertical). In this experiment, only one of the displays was activated, providing for monocular viewing.

For the generation of the graphic images, a Sun Sparc II workstation was used; the graphics update rate used here was 33 Hz while the screen refresh rate was 66 Hz. Because the HMD required NTSC video input, we had to convert the graphic images generated by the Sun. A simple way to perform this conversion is to "capture" the screen image from the computer with a video camera that outputs NTSC. We used a Sony color CCD video camera (model V701) to do exactly that. By rendering a sufficiently large image on a Sony Trinitron monitor connected to the Sun, and then capturing that image with the video camera, we were able to deliver NTSC video to the HMD with little loss in image quality. (The primary factor limiting the quality of the Sun-rendered image as seen by the subject was the LCD display resolution). The video camera has an adjustable shutter; we found that a 60 hz shutter speed gave optimal results. Although it resulted in a temporal alias of 6 Hz with the 66 Hz refresh rate of the Sun display, the relatively sluggish response of the LCD display kept the alias from being very noticeable.

Tracking of the subject's head movements was accomplished using a combination of two sensing systems, one to sense position and one to sense orientation. For position sensing, we used a custom-built 2D video tracking system that can determine the location of a point light source within a horizontal plane at video refresh rates[6]. By positioning a light source on top of the HMD, we were able to track the location of the subject's head as he/she translated laterally with a precision of better than 3.0 cm and a latency of 17 ms. For orientation sensing, we used a fluxgate compass (Etak 02-0022) mounted on the helmet. This electronic compass outputs azimuthal angle with a precision on the order of 1° and a latency of less than 10 ms. This device gives an accurate measurement of head azimuth, however, only if head rotations are confined to the vertical axis. This condition was met in the present experiment because all stimuli were generated at eye-level, and thus there was no tendency of the subjects to pitch their heads up and down.

Both of the head sensors were interfaced to a 50 MHz 386 computer; a Scientific Solutions Labtender board was used to sample the digital output of the position sensor, and an Avantek board was used to sample the analog output of the orientation sensor. Each sensor was sampled by the PC at 33 Hz (the graphics update rate of the Sun workstation), and the data about the subject's head position and orientation were transmitted at 33 Hz to the Sun workstation via an ethernet connection. We tested the latency of the entire system by electromagnetically activating the fluxgate sensor and measuring the delay for a corresponding update in the HMD to be detected by a photo-diode. Using this procedure we calculated a total system lag time of 90 ms. With such a short system lag, subjects report visual lags only when rotating the head quite rapidly. We feel that this is sufficiently short to allow us to effectively simulate viewing of the physical spheres in the real environment.

2.3 Visual stimuli

In both the Real and Virtual environments, the subject saw a glowing sphere at eye-level in darkness. Depending on the size and distance of a particular stimulus configuration, the visual angle of the sphere's circular image ranged from 1.2° to 3.7°. The real spheres were always stationary in the room as were the simulated spheres in the virtual environment; absolute motion parallax was generated as a consequence of subjects' lateral head translation, for the subject moved 1 meter to either side of the starting position while viewing the stationary target. For the nearest object distance (100 cm), lateral motion induced an absolute motion parallax of 90° for the full 2 m excursion of the head. For the farthest object distance

(405 cm), this value was reduced to 28°. Subjects were instructed to translate their head at a rate such that there were able to complete about 3 cycles during the 10 sec observation interval.

The only other source of distance information besides absolute motion parallax was expansion and contraction of the spheres' circular images. During lateral translation of the subject, the distance between the subject and the sphere increased as the subject moved away from the center position. This in turn produced a contraction of the sphere's image, to be followed by an expansion of the image as the subject returned to the center position. At the farthest point of lateral translation (100 cm), the percent changes of the image's diameter for the four object distances of 100, 174, 264 and 405 cm were 29%, 13%, 6.5%, and 3.0%, respectively. These changes in angular size are sizeable enough to provide additional information about target distance beyond the absolute motion parallax considered to be of primary importance.

Physical Distance (cm)

Physical Size (cm)	100	174	264	405
3.66	2.10°	1.21°		
6.37	3.65°	2.10°	1.38°	
9.68		3.19°	2.10°	1.37°
14.83			3.22°	2.10°

Figure 2. The stimulus combinations used in the experiment. Combinations of size and distance used are indicated with a corresponding visual angle
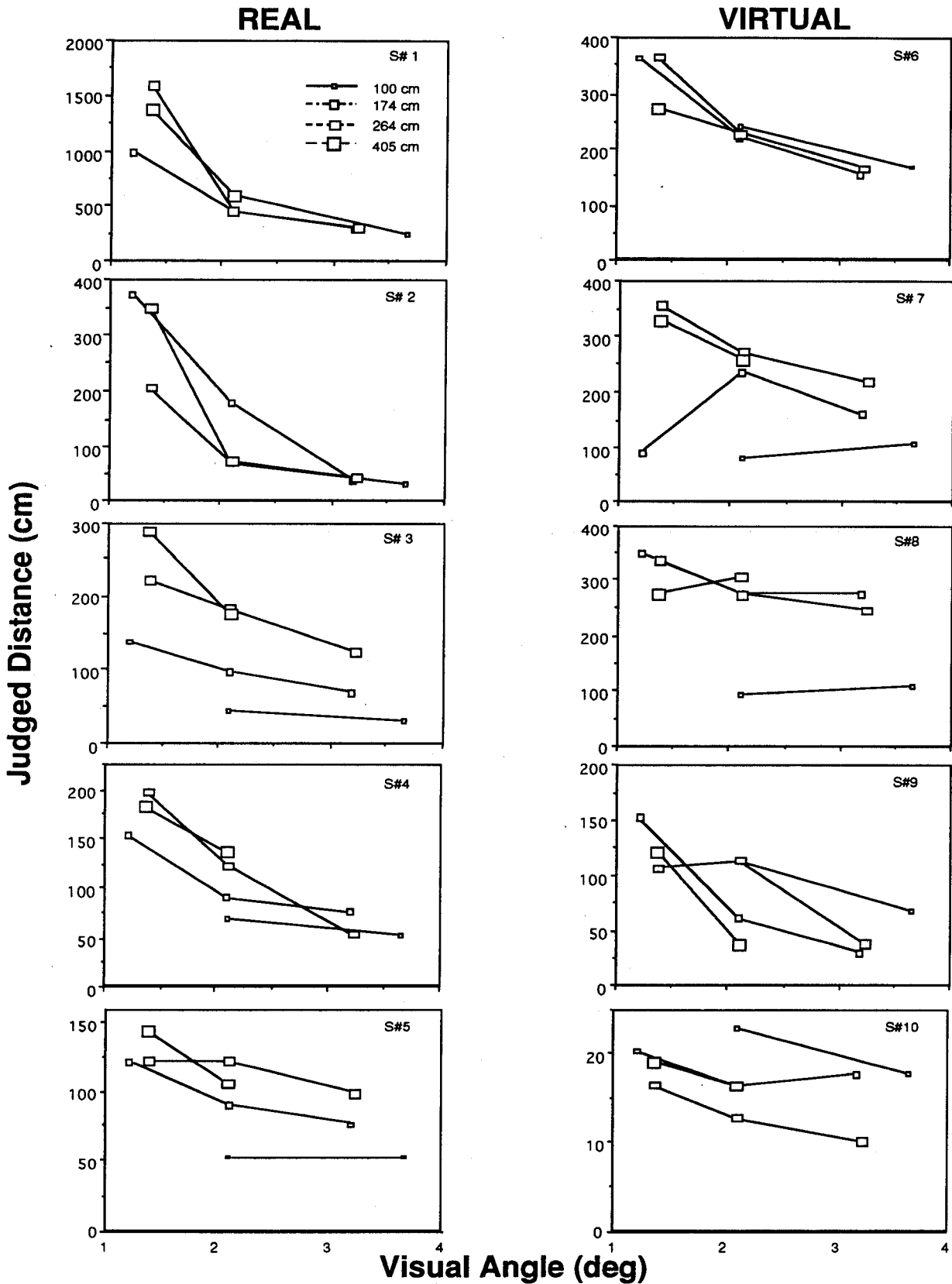
2.4 Design

Two independent variables were manipulated in this experiment in a within-subjects design. The first is sphere size. We used four different spheres with physical (and simulated) diameters of 3.66, 6.37, 9.68, and 14.83 cm. For the second independent variable, we chose four distances (100, 174, 264, and 405 cm) such that when the respective spheres were positioned at these distances, they were projectively equivalent (i.e., of constant visual angle). In addition to these four configurations, six other size and distance combinations were used as stimuli in the experiment (Figure 2).

In addition to the within-subject variables described above, the comparison of Real and Virtual environments mentioned earlier was carried out as a between-subjects manipulation. Half of the subjects were tested in the Real condition, while the other half were tested in the Virtual condition.

Three dependent measures were recorded: judged size, judged distance, and judged illusory motion. We will not be concerned with the motion judgments in the analysis.

2.5 Procedure

Each subject was met outside the laboratory and instructed on the experimental procedure. The subject was told that he/she would be led into the room with his/her eyes shut so that the experimental setup could not be seen. Once led into the room, the subject first faced a wall opposite the experimental setup. Here the subject was to remain staring at this white wall until the rooms lights were turned off as well as during subsequent periods between trials, thus preventing the subject from dark adapting very much. Once the lights went out, the subject was to close his/her eyes and turn 180°, grasp the taut guide-rope that would be used as a guide during lateral translation. At this point the experimenter announced the type of judgment to be made for that particular trial (size, distance, or motion). Then, upon command by the experimenter, he/she was to open the eyes, look at the glowing sphere floating directly ahead in the room, and begin translating sideways until a stop in the rope was encountered. Upon reaching the stop, the subject was to reverse direction and move until the opposite stop was felt. This process was to be repeated until 10 sec had elapsed, during which period the subject was to attend carefully to the glowing sphere. At the end of 10 sec, the experimenter instructed the subject to close the eyes before the room lights were turned on.

Before beginning the experiment, the experimenter carefully explained each type of judgment. For the size judgments, subjects were instructed to indicate perceived size using the lateral separation between the two index fingers (which would then be measured with a ruler). It was stressed that physical target size, not retinal size, was to be judged;

REAL   **VIRTUAL**

Figure 3. Individual subject data for the distance judgments.
Each data point corresponds to the mean of two responses

REAL

VIRTUAL

Judged Size (cm)
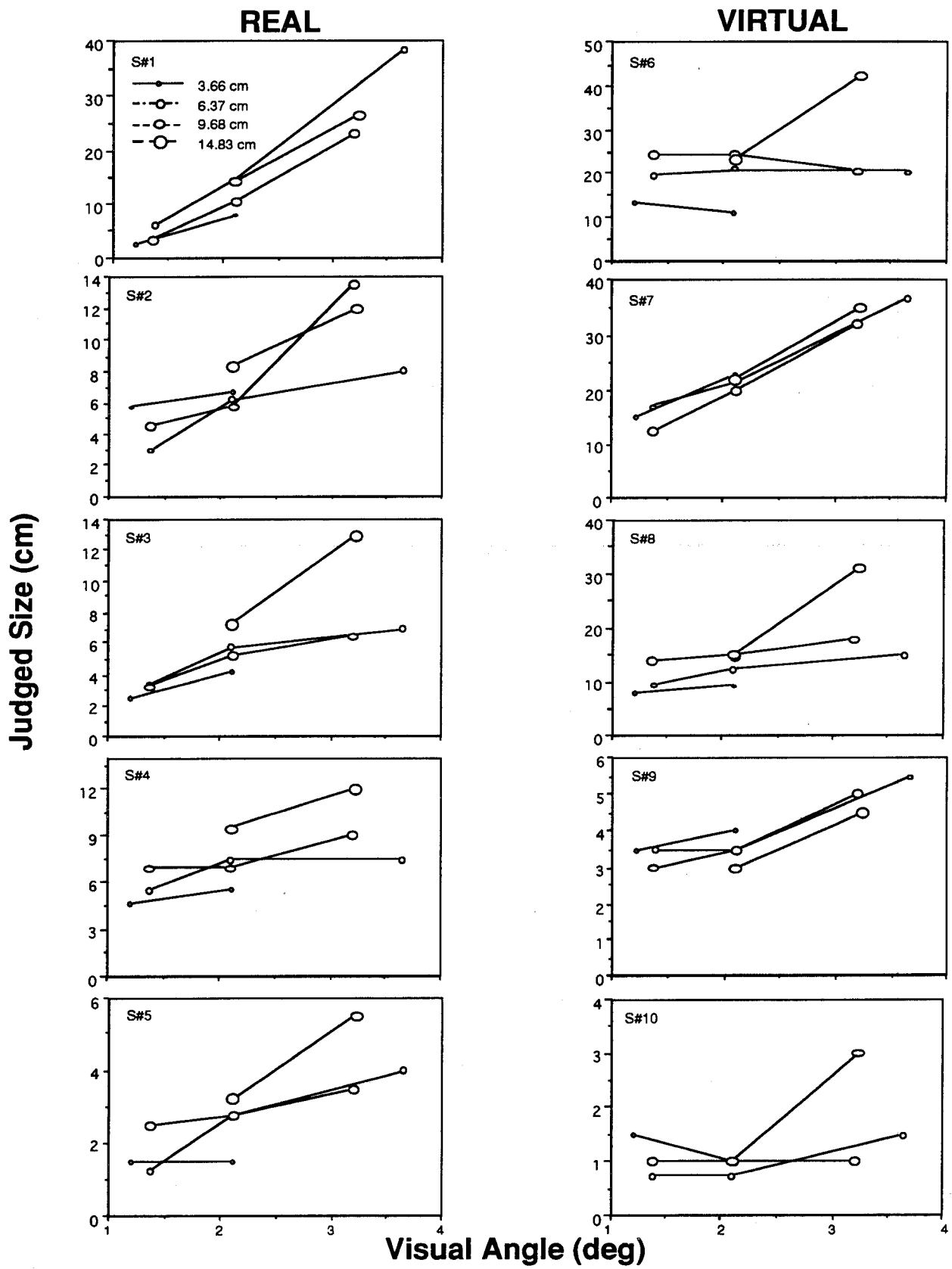

Visual Angle (deg)

Figure 4. Individual subject data for the size judgments.
Each data point corresponds to the mean of two responses.

they were told to indicate the size that would be correct if they were allowed to walk up to the object and grasp it. For the distance judgments, subjects were told to verbally report the distance to the glowing sphere (in feet or whatever scale units were preferred). Finally, for motion judgments, subjects were told to report the amount of perceived object motion, if any, using the same manual adjustment procedure used in the size judgment. We will not devote further attention to these motion judgments.

Each of the ten stimulus configurations was repeated twice for each of the three response types, for a total of 60 judgments per subject. The order of the stimulus configuration and response type was randomized. It took an average of one hour to complete the entire experiment.

3. RESULTS

Figures 3 and 4 give the distance and size judgments, respectively, of the individual subjects. Each panel plots the judged distance against the visual angle of the stimulus object. Different sized symbols are used to distinguish spheres of differing size (at differing physical distances), thus corresponding to differing amounts of absolute motion parallax. Each data point represents the mean response of two trials. The subjects in the left column of each figure participated in the Real conditions while those in the right column participated in the Virtual conditions. Note that the scale markings of the ordinates vary from subject to subject, indicating wide variation among the subjects in the scale of their judgments.

In order to obtain meaningful averages of these size and distance judgments, in view of the large subject-to-subject variation, we normalized the data before taking means. To illustrate, consider the distance judgments obtained in the Real environment. The mean values were obtained for each subject and then averaged to obtain the grand mean. The ratio of the grand mean divided by a given subject's mean was then used to rescale that subject's values, so that each subject's normalized values had a mean equal to the grand mean. These normalized values were then averaged to give the mean values in Figures 5 and 6. This normalization procedure gives more or less equal weight to each of the subject's data, assuming that the main source of variation between subjects is the use of different response ranges.

4. DISCUSSION

The results given in Figures 5 and 6 can be compared with the predictions of the two hypotheses stated earlier. The fact that the curves for different physical objects separate vertically both for judged distance (Figure 5) and for judged size (Figure 6) implies that subjects did use absolute motion parallax in their judgments, for otherwise the curves would coincide, there being no other basis for discriminating distance (and size). At the same time, however, it is clear that
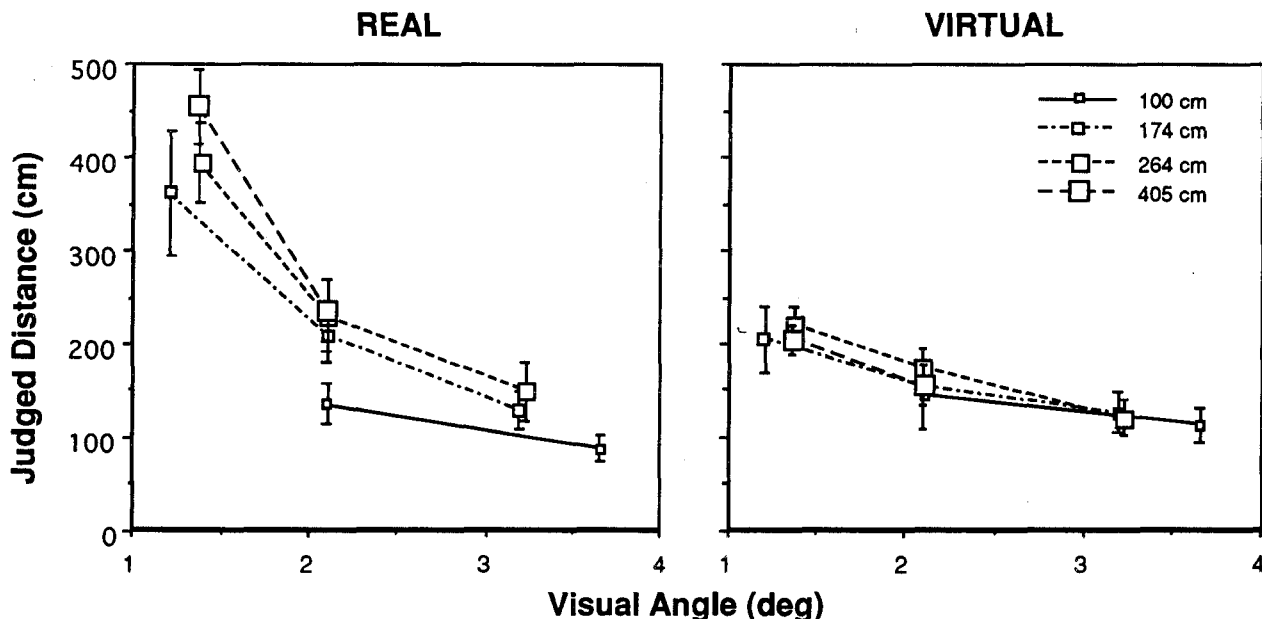

Figure 5. Means based on the subjects' rescaled data for the distance judgments.

absolute motion parallax, which has high signal value in this experiment, only weakly determines the perception of size and distance. This is most apparent for those configurations matched in visual angle with a value of 2.1°. If absolute motion parallax were to correctly determine the perception of size and distance, the different judged sizes and different judged distances would vary by a factor of 4.0 (as in Figure 1). Instead, judged distance varied by a factor of only 1.74 and 1.07 for Real and Virtual environments, respectively; similarly, judged size varied by a factor of only 1.66 and 1.18 for Real and Virtual environments, respectively.

Before accepting the conclusion that absolute motion parallax is a weak determinant of visual scale, we should note that angular size was probably counteracting the influence of absolute motion parallax. Although subjects were told that the stimuli were of different sizes, thus reinforcing the limited signal value of angular size as a cue to size and distance, subjects were influenced by its variation, as can be seen by the general downward trend from left to right in the figures involving distance judgment. By virtue of its constancy across conditions where target size and distance were varied, angular size must have been exerting some opposing influence (signifying constant size and distance) in these conditions.

Even so, the experiment does show that absolute motion parallax is not a strong cue to egocentric distance, for angular size is itself rather weak. Consider two objects of constant angular size placed in a room, one much larger than the other but viewed from a correspondingly larger distance. The objects indeed look very different in size even with stationary monocular viewing, provided that a variety of static distance cues, like height in the field, are available[7]; indeed, they can look so different in size that considerable persuasion is needed to convince naive observers that the objects share something in common, namely, angular size. Thus, angular size can be easily overridden by other cues, signifying that it is rather weak. That the absolute motion parallax in this experiment, ranging from 28° to 90° during a single excursion of the head causes only mild variation in judged size and distance, albeit in the presence of the opposing influence of angular size, is an indication of its ineffectiveness as well. Other research confirms this conclusion that the absolute motion parallax associated with lateral movements of the head, in the absence of specific training, is a weak determinant of perceived egocentric distance and size[7, 8, 9, 10]; in particular, the study by Gogel and Tietz[9] concluded that absolute motion parallax is about as strong a cue as accommodation, but weaker than convergence.

In the experiment we have reported, head translations were always perpendicular to the initial line of sight to the target. This procedure was followed to limit the optical motion produced by head translation primarily to changes in the target's angular direction. However, because distance to the target did vary slightly, there was some optical size change of the target as well, which probably influenced the subject's judgments. We can ask, however, whether motions of the head toward and away from objects might have produced more accurate judgments of size and distance than do lateral motions of the head. Although we have not conducted a formal experiment on this question, informal observations with the virtual
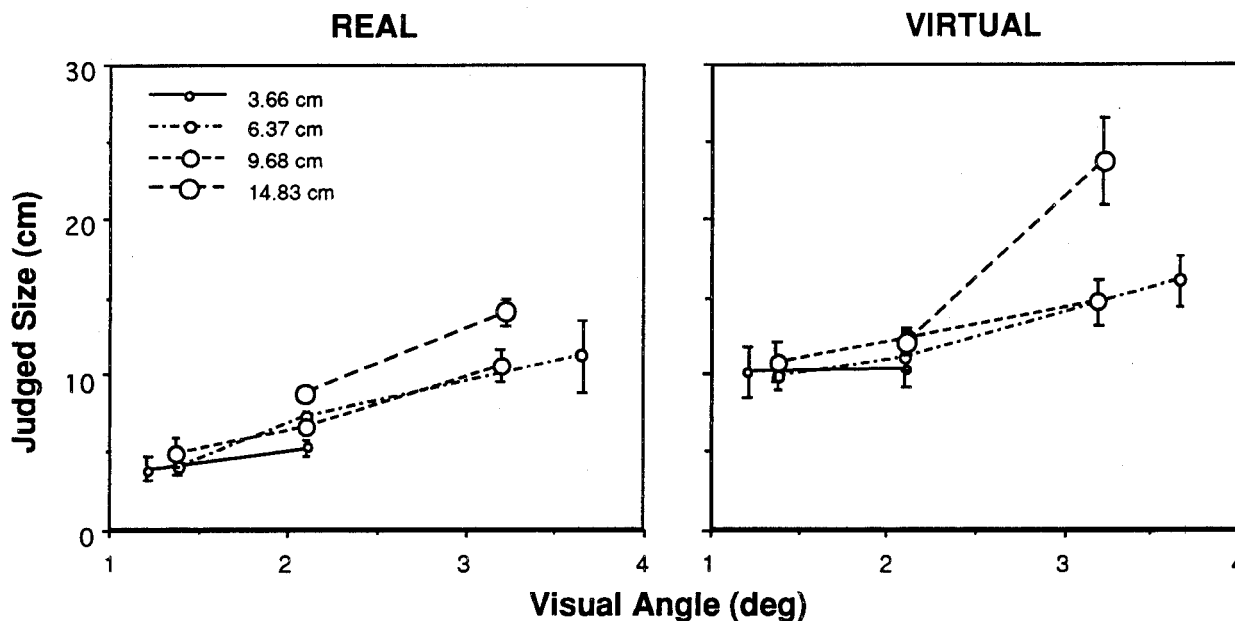

Figure 6. Means based on the subjects' rescaled data for the distance judgments.

display suggest that approaching/receding motions of the head do not result in noticeably more accurate perception of objects than do lateral motions.

Confirming the relatively weak effect of absolute motion parallax (and of optical flow in general) in determining visual scale are other observations we have made with our virtual display. Even when the virtual environment is filled with objects, changing the gain of the head tracking system so that a given physical movement of the head results in differing amounts of movement of the simulated eyepoint does not cause a perceptual rescaling of the virtual environment. Rather, substantially increasing the gain of head translation gives rise to the strong impression that the environment is "in motion" so that forward observer motion results in the impression that the virtual environment is moving rapidly by in the opposite direction; Gogel[10, 12] has provided a compelling analysis of this apparent motion of objects accompanying translation of the head.

How then do observers assess visual scale, both in real and virtual environments? Certainly, accommodation and convergence can serve as indicators of absolute scale, at least for near distances. Given an object in the near foreground whose size and distance are specified by these cues, binocular disparity can be used to extend the calibration of visual space out to larger distances. However, as noted in the introduction, the importance of binocular information in visual space perception has been overrated, for moving around in real environments with monocular viewing leads to an experience that differs little from that with binocular viewing. Height in the field (angular elevation) would seem a good candidate for determining the distance and size of objects; indeed, Philbeck and Loomis[7] have shown it to be a strong determinant of perceived distance. However, even this cue can only be of limited use, for its signal value drops to zero when one relaxes the assumption that the eye is at normal eyeheight. Similarly, familiar size would seem a good candidate for establishing visual scale, but a number of researchers[13, 14, 16, 16] have found that familiar size exerts only a weak influence on the perception of size and distance.

This consideration of each of the potential egocentric distance cues leads to the conclusion that no single cue is a completely reliable indicator of visual scale. Of course, the possibility remains that a number of partially reliable cues operating in concert might lead to an unambiguous determination of visual scale. But there is still another possibility. Aside from accommodation and convergence, all of the other cues to absolute scale are subject to assumptions on the part of the observer (absolute motion parallax: stationarity of objects; height in the field: the eye is at normal eye height; familiar size: the object is its normal size; relative size: each element is of the same distal size). It may be that observers participating in laboratory experiments are willing to relax one or more of these assumptions because they know that the experimenter is able to arrange contrived stimulus configurations that violate the constraints of everyday experience. In this view, the results of laboratory experiments may not generalize to ordinary experience, where the assumptions are presumably maintained by the observer. This view that observers are able to relax their assumptions is, of course, antithetical to the view held by most researchers in perception--that the perceptual system is largely impenetrable to cognitive influence. However, if there is truth in it, it may mean that research using virtual displays will be even less applicable to the understanding of ordinary perceptual experience than earlier laboratory research, for the observer entering a virtual environment might well assume that "anything is possible". Perhaps for this reason, changing the gain of the head tracker results in apparent motion of the virtual environment rather than a change in its apparent scale.

5. ACKNOWLEDGMENTS

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